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Comparative analysis of satellite-based and ground-based lightning detection data during 2013-2016 in China

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According to the location of sensors, there are two main ways to obtain lightning detection data : satellite-based and ground-based, each have its own advantages and disadvantages, the assessment of data quality is an important issue. In this paper, based on comprehensive analysis of the data from satellite- and ground-based detector (2013-2016), a sensitivity test is designed, and a scientific comparison method is proposed. From multiple dimensions, the differences and similarities between them, the sources of error and the method of correcting are investigated. Through the comparative analysis, we can get more information on spatial and temporal lightning distribution characteristics in China the following conclusions are drawn: 1. satellite- and ground-based lightning detection data over China show good consistency during 2013-2016, and with the development of technology and the improvement of detection stations layout, the proportion of matches go up steadily. Furthermore, limited by geographical factors, the layout of China Lightning Detection Network (CLDN) is uneven, the East is comparatively dense, and West is comparatively sparse, so the matching ratio is not exactly the same. We also noticed that Lightning Imaging Sensor (LIS) cannot continuously monitor the evolution process of lightning, and it's a reason that the proportion of matches are not very high in general. 2. Matching proportion shows obvious time diversity. It presented a single peak in August. Matching proportion among seasons as follows: summer-autumn-spring-winter (from high to low), in particular, it had less variability during winter and spring than summer and autumn, reflecting the characters of strong convective weather in China. 3. Due to the different detection principles, the amount of lightning events that occur at "night" detected by LIS, much more than lightning events that occur in the "day" time. While the situation is completely different for CLDN, there was no significant difference in the amount of lightning that occurs between day and night, and there is still a lot of space for improvement. 4. Sample data revealed that larger radiance LIS signals did not mean a higher matching ratio, this is different from conventional wisdom. It may imply that satellite-based detection and ground-based detection are sensitive to lightning signals with different radiation levels.

The work of this paper also provides the basis for the quality evaluation and fusion analysis of the satellite-based vs. ground-based multi-source lightning detection data.

[Key words: Ground-based, Lightning characteristics, Lightning detection, Satellite-based]

Introduction

Lightning, one of the most important and spectacular weather phenomena in nature since ancient times, and has a significant impact on people's lives, social activities and economic production. The characteristics of lightning activity have always been an interesting topic, and the lightning data provides an important basis for related research. Different features of lightning provide theoretical basis for multi-angle detection. Currently, according to the location of sensors, there are two main ways to get lightning detection data : satellite-based and ground-based[1]. Based on the spectral radiation characteristics of lightning signal, satellite-based lightning detection can be realized[2], while the ground-based detection based on electromagnetic propagation features. Each method has its own advantages and disadvantages. Thus, multi-source data quality assessment is an important issue. Furthermore, based on the assessment, the fusion application of multi-source detection data can make people understand lightning from more angles.

Satellite-based lightning detection has such advantages as wide observation range, high observation angle, not subject to ground conditions, etc. Intuitive and dynamic lightning observation data can be obtained. According to the height of the orbit, it can be divided into low Earth orbit (polar-orbiting) lightning detection and high Earth orbit (geostationary-orbiting) lightning detection. The former began in the mid-1990s, is represented by the Lightning Imaging Sensor (LIS), observing optical pulses around the globe produced by the lightning[3]. Now its data is still widely used. The shortcoming of polar-orbiting satellite-based lightning sensor is that due to the feature of platform, it keeps flying from the North Pole to the South Pole; it's hard to stay at one point for a long time (only about 90s). As a result, it is difficult to detect all the lightning that occurs in a given area. Therefore, the detection accuracy is limited by the orbital period; it can only provide average information on lightning distribution in a certain region. High Earth orbit (geostationary-orbiting) lightning detection is represented by GLM (Geostationary Lightning Mapper) for USA, carried by GOES-R satellite, and LMI (Lightning Mapping Imager) for China, carried by FY-4A, can provide consistent observations over a large area, including China and the surrounding waters. LIS data can be used as ideal test data for LMI. The work of this article also provides the basis for their data testing and validation.

Ground-based lightning detection in China, represented by China Lightning Detection Network (CLDN), built in 2007, as a national lightning ground-based detection network, includes the national lightning data processing center, and is employed to gain insight into the spatial and temporal distribution of the cloud-to-ground (CG) lightning in the China. The data shows that CG lightning activities in China vary from season to season, including positive CG and negative CG. Its accuracy is restricted by the factors such as uneven location of the detection stations and signal attenuation, etc.

With the continuous development of detection technology, more and more attention has been paid to the quality evaluation and reliability test of data obtained by different methods. Due to the detection principle and technology are different, there is a significant difference in units、range resolution and format between the data derived from satellite-based and ground-based lightning detection methods. Foreign scholars have done some work in this field, such as Finke *et al.*[4] analyzed the ground-based lightning detection data and satellite-based data from LIS in Europe; Daile Zhang *et al.*[5] focused on the differences between NLDN (short for National Lightning Detection Network) and LIS, and the efficiency improvement after 2013 was analyzed; Kelsey B. Thompson *et al.*[6] carried out the comparative analysis between the data from two ground-based lightning detection networks and from satellite-based LIS. However, these studies cover a relatively short span of time, and their results are not applicable to China due to lots of differences such as geographical environment、the distribution of the detection stations, etc. Therefore, it is very necessary to carry out a systematic evaluation of multi-source lightning detection data in China, and providing support for the further use of fusion analysis.

Comprehensive analysis of CLDN and LIS (2013-2016 in China) was carried out in this paper. A sensitivity test is designed, and a scientific comparison method is proposed. From multiple dimensions, the differences and similarities between them are researched; the sources of error and the method of correcting are investigated. Through the comparative analysis, we can learn more about the lightning characteristics in China, and the work of this paper also provides the basis for the quality evaluation and fusion use of the satellite-based vs. ground-based multi-source lightning detection data.

Materials and Methods

A. LIS

LIS, short for Lightning Imaging Sensor, is an instrument aboard the Tropical Rainfall Measuring Mission (TRMM) satellite[7], which was designed to study lightning climatology and thunderstorm processes. It ended observation mode on April 8, 2015. Its data is now widely used, and with substantial findings. TRMM was a polar-orbiting satellite; it took about 96 minutes to go around the earth. Limited by the feature of platform, it's difficult for LIS to stay at one point for a long time; the data of 16 channels is obtained every day. LIS can detect all types of lightning. LIS used a CCD array[8] (short for Charge Coupled Device) to detect the lightning.

RTEP[9] (short for Real Time Event Processor) was used on LIS, extracting real lightning signals from background noise by threshold discrimination[10]. For the convenience of data processing, a data processing algorithm[11] is used. LIS data is divided into three types: events, groups and flashes[12].

Foreign researches have compared the lightning detection data between LIS and ground-based networks. Thomas *et al.*[13] calculated the efficiency of LIS in New Mexico, and when they shifted LIS location North 6 km, it obtained the best spatial agreement; Ushio *et al.*[14] discovered the detection activities of LIS in CG lightning and IC lightning, respectively. There are only a few relevant studies in China, and since foreign results cannot be applied to China, there is a requirement to strengthen it further.

B. CLDN

National ground-based lightning detection in China, included 357 sensors over the most land of China[15]. Lightning stroke radiates electromagnetic pulses, which spread to detection stations thousands of kilometers away. Therefore, ground-based lightning detection locates lightning source by simultaneously measuring electromagnetic pulses from multiple stations, using the methods such as MDF (Magnetic Direction Finder), TOA (Time of Arrival), IMPACT (IMProved Accuracy from the Combination of MDF and TOA Technology)etc.[16].

After preprocessing, CLDN generates the data in .txt format, each record represents a lightning stroke[17]. The average detected distance of a sensor is approximately 300 km, and the location accuracy of the network is approximately 300 m. The detection efficiency of the network is more than 80 %[18]. The uneven distribution of the detection stations restricts the improvement of detection efficiency, for example, the detection efficiency may be lower in northwestern than in southwestern due to lack of sensors.

As a national unified network, it can analyze the spatial and temporal characteristics of CG lightning over the most land of China based on the unified equipment and data processing algorithm. Data consistency is one of its advantages over other provincial ground-based lightning detection networks, and it is also the reason we choose it for analysis. As the network continues to optimize, the data was relatively complete after 2009. The data include the following information: date, time, location (latitude and longitude), polarity, intensity and peak current.

C. Methods

Due to the differences in principle, algorithm, format, units and range between the satellite-based and ground-based lightning detection data, in order to provide more efficient use of data, the method and criteria of matching should be established first[19].

All of the lightning detection data derived from two sources in the dataset, 2013-2016, was analyzed to find coincidences. We designed a sensitivity experiment, including many factors, then the matching criteria were chose as follows: for a LIS group and CLDN stroke, the time threshold: $\leq 1.0s$, the distance threshold: $\leq 0.5^\circ$ (latitude), $\leq 0.5^\circ$ (longitude), they are considered to be matched in this range. Define matched percentage (MP) for satellite-based and ground-based lightning detection data as: in the chosen region and time interval, LIS groups, which can coincide with at least one ground stroke, account for the proportion of the total number of LIS groups in the research range. The MP value equal to 100 % means that each LIS group has at least one matching (consistent) ground stroke. The MP value of 0 means that none LIS group has matching ground stroke. By adjusting the matching windows continually, MP values were counted based on different time and distance intervals. An example of the MP algorithm is shown in Figure. 1, we want to adjust the matching windows constantly to find the change rule of MP value, in order to not miss any possible coincidence, according to the principle of "match proportion as high as possible", we choose the match “windows” for time and space as large as possible.

As shown in Figure 1, in the entire region, MP values were calculated based on certain distance constraints and a varying time constraint. To establish time match criteria, the time interval between the satellite-based and ground-based data is from 0.2 seconds to 1.2 seconds, with 0.2 seconds as the granularity. As shown in Figure 2, in entire region, MP values were calculated in different distance constraints. To establish space match criteria, the latitude and longitude interval between the satellite-based and ground-based data is from 0.1° to 0.6° with 0.1° as the granularity.

From Fig. 2 and Fig. 3, we can draw a conclusion: MP increases with the space-time interval. We found the time and distance threshold, which make these curves flattened. It means that MP values no

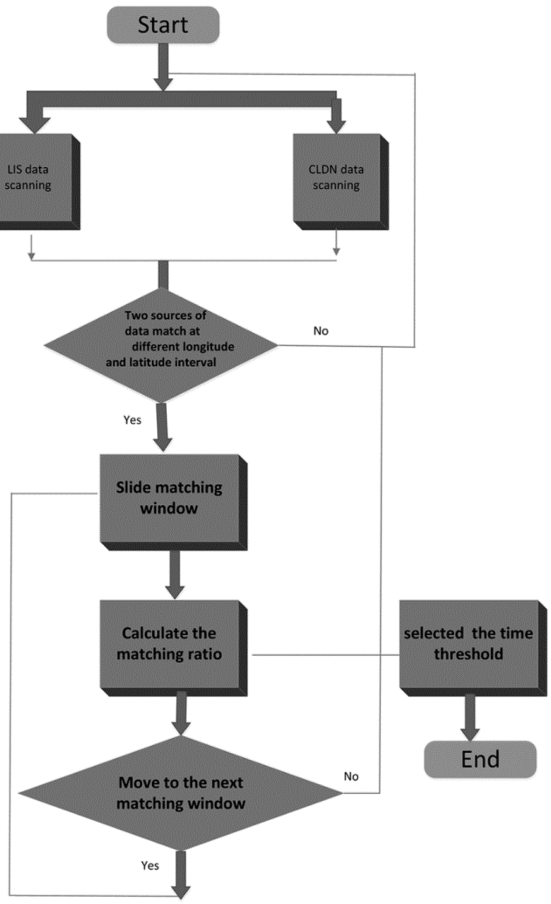

Fig. 1 — Flow chart of time match criteria algorithm for LIS and CLDN data

longer increase as the allowed time \latitude\longitude differences increased. This point is considered as "match window". If a LIS group has more than one matching ground stroke, the MP value should not be calculated twice.

Results

To learn more about the characteristics of lightning activities over China, in this study, based on the sensitive test and the matching criteria, we have analyzed the data (2013-2016) derived from satellite-based and ground-based lightning detection technologies, LIS vs. CLDN. Over this 4-year time period, MP values showed large spatial and temporal variability. From four dimensions of year, season, diurnal variations and signal radiance, multiplicity comparison between two sources of data were performed, the factors causing the differences were discussed, and provide the basis for the quality evaluation and fusion use of the satellite-based vs. ground-based multi-source lightning detection data.

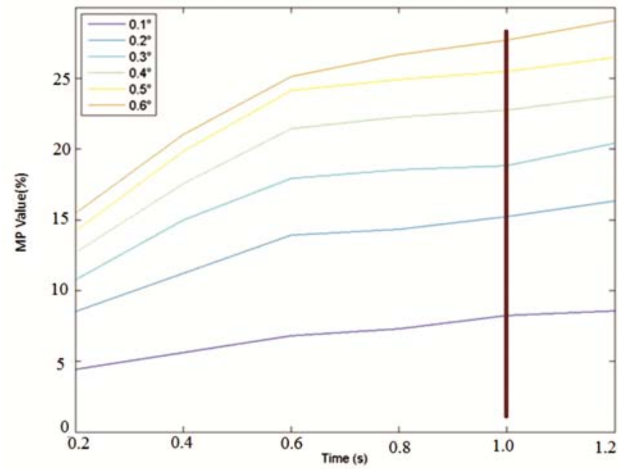

Fig. 2 — The establishment of time match criteria

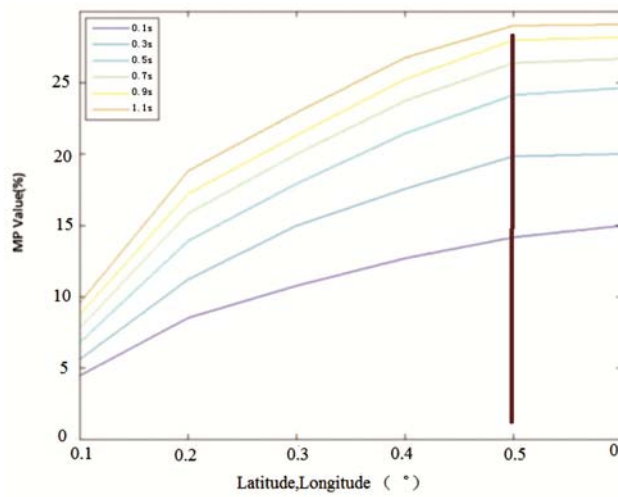

Fig. 3 — The establishment of spatial match criteria

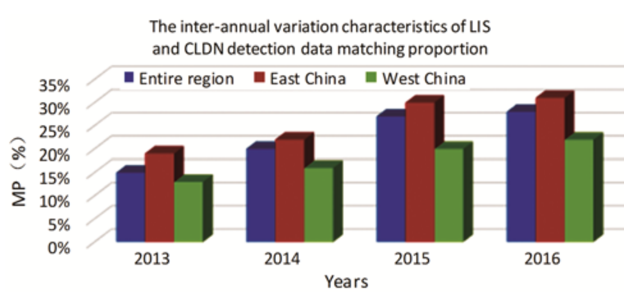

Fig. 4 — Inter-annual variation characteristics of LIS and CLDN detection data matching proportion

Discussion

A. Inter-annual variation

As shown in Figure. 4, according to the matching algorithm we discussed above, the inter-annual variation characteristics of satellite-based and ground-based lightning detection data matching proportion are analyzed from three geographical subregions: entire China, Eastern China, and Western China.

The results demonstrated that satellite-based and ground-based lightning detection data over China showed good consistency during 2013-2016, reflecting the spatial and temporal lightning distribution characteristics in China. With the development of technology and the improvement of detection stations layout, the MP values went up steadily, especially after 2014, the layout of CLDN tended to be fixed and perfect[20], MP values increased greatly and tended to be stable. The result proved that the long time series of LIS data can provide "average" information on the lightning distribution in China. Furthermore, limited by geographical factors, the layout of CLDN is uneven, the East is comparatively dense (20° N-38° N, 104° E-120° E), and the West is comparatively sparse (29° N-38° N, 74° N-100° E)[21], so the higher MP values were located in the East part of China.

Meanwhile, we also noticed that the staring time (observation time) of any place on the earth is extremely short (about 90 seconds) because of the limitation of orbital period[22,23], so the observation range of LIS is limited. It's only when the satellite scans the lightning that's happening at the exact site, it can be detected[24,25]. It means that LIS cannot continuously monitor the evolution process of lightning[26], and that's why there are differences in detection capabilities of LIS and CLDN, and thus, the MP values are not very high in general. In addition, LIS realized detection of all kinds of lightning, it cannot distinguish the type of lightning[27], while CLDN can only detect CG at present, and this is also one of the reasons why the two data matching ratio is not high. All of these factors mentioned above also provide main improvement direction of LMI for geostationary orbit platform.

B. Seasonal variation

Seasonal variation characteristics of MP values between CLDN and LIS are shown in Figure 5. MP values showed large temporal variability. It presented a single peak, matching proportion reached the highest in August. Matching proportion among seasons as follows: summer-autumn-spring-winter (from high to low), in particular, it had less variability during winter and spring than summer and autumn, reflecting the characters of strong convective weather in China.

Diurnal variations

LIS data recorded in UTC (Universal Time Coordinated), while CLDN data recorded in BTC (Beijing Time Coordinated), for convenience of research, we unified the two different formats, and defined 7:00-19:00 (Beijing time) as "day" and the rest as "night". Lightning distribution during "day" and "night" in China (2012-2015) from LIS and CLDN data was shown in Figure 6.

The comparison between LIS and CLDN can be seen from the figure. The amount of lightning events that occur at "night" detected by LIS, was much more than lightning events that occurr in the "day" time. While the situation is completely different for CLDN, there was no significant difference in the amount of lightning that occurs between day and night. The annual average MP value between LIS and CLDN was 20 % (night) vs. 10 % (day), this is because the detection principle of LIS is based on optical imaging, and the extraction of lightning signals in daytime has always been one of its main technical difficulties.

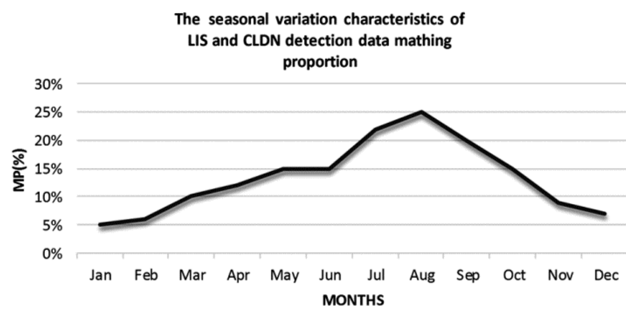

Fig. 5 — Seasonal variation characteristics of LIS and CLDN detection data matching proportion

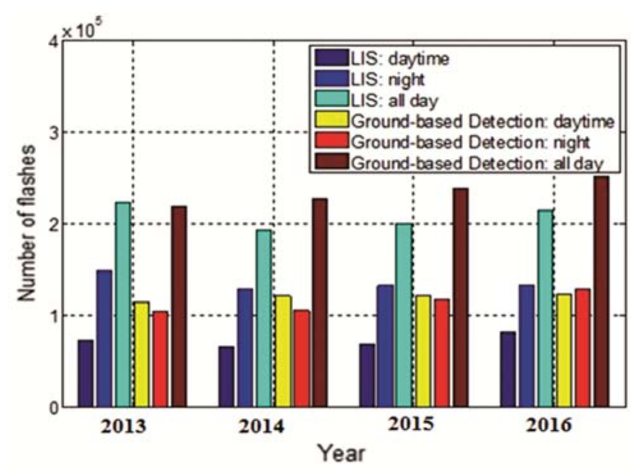

Fig. 6 — Diurnal variations in lightning distribution in China

Due to the amount of sunlight reflected at the top of the cloud is much stronger than the amount of radiation produced by lightning, lightning signals in daytime often overwhelmed by background noises. Therefore, when it comes to daytime lightning detection, it is very necessary to make full use of the differences in time, space and spectrum characteristics of the lightning signal and noises, enhancing the maximum of lightning signals relative to the bright background.

Although LIS has the function of adjusting the judge threshold of lightning signals according to the change of background radiation condition, which improved the efficiency of lightning detection in daytime to some extent, there is still a certain gap between CLDN, and there is still a lot of space for improvement. It is also a major challenge for LMI.

The comparison of lightning detection signal radiation

A mean of 10 %, 20 % and 12 % of 20 larger radiance LIS detection data per day had a matched CLDN stroke in west, east and entire China respectively, in the period of this research section.

Sample data revealed that larger radiance LIS signals did not mean a higher matching ratio, this is different from conventional wisdom. It may imply that satellite-based detection and ground-based detection are sensitive to lightning signals with different radiation levels. This may be one of the fundamental differences between the two detection technologies.

Conclusion

In this paper, CLDN data and LIS data (2013-2016) over China were compared and temporal and spatial variability were found. According to the principle of "match proportion as high as possible", a sensitivity test was designed, based on the results of the test, the matching criteria was established. The definition of MP is proposed, and then over the period of research, MP values showed large spatial and temporal variability. From four dimensions of year, season, diurnal variations and signal radiance, multiplicity comparison between two sources of data were performed; the factors causing the differences were discussed, and provide the basis for the quality evaluation and fusion use of the satellite-based vs. ground-based multi-source detection data, which will be more helpful to the study of lightning and strong convection weather.

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